Redeveloping a Readout System for Particle Tracking at Fermilab's Test Beam Facility

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Abstract

Fermilab's Test Beam Facility provides national and international users with access to accelerated particle beams for individual detector experimentation. Experimentalists may use the primary beam for 120 GeV protons; secondary beam for 1 GeV pions, muons, and electrons; or the tertiary beam for 200 MeV pions and protons. In order for users to calibrate their detectors, they compare their results to those of the instrumentation provided by the facility to test triggering, tracking, and particle identification capabilities. This instrumentation includes scintillator counters, multiwire proportional chambers (MWPCs), Cherenkov detectors, segmented wire ionization chambers, time-of-flight systems, Silicon pixel telescopes, and lead glass calorimeters. Due to advancing technology, the existing electronics and readout systems have become obsolete and are being not only upgraded, but entirely redeveloped. The new MWPC software is written in Python and is designed to communicate with a Wiener CC-USB CAMAC controller to collect particle data, to set threshold configurations, and to handle errors through a system of diagnostic debugging.

1. Introduction

1.1 Fermilab's Test Beam Facility

Originally part of Fermilab's fixed-target program in the 1970s, the Meson Laboratory was repurposed in the early 2000s to be an experimentation site open to any scientist requiring the use of high-energy particle beams.[4] Following its transformation as Fermilab's Test Beam Facility (FTBF), the laboratory is one of only two high-energy hadron test beams in the world, and is the only such site in the United States.[7]

FTBF allows researchers to test their detectors using three beam types: the primary beam for 120 GeV protons, the secondary beam for 1 GeV pions, muons, and electrons, and the tertiary beam for 200 MeV pions and protons. Different experiments call for different energies and intensities, and FTBF strives to accommodate the needs of visiting experimenters.

The facility also provides its own instrumentation to visiting researchers for the purpose of calibrating user prototypes. By comparing the results of their devices with those of the provided particle tracking instrumentation, users can ensure they implement the correct thresholds, trigger timing, and identification methods for their projects. The types of instrumentation provided by the facility include scintillator counters, multiwire proportional chambers (MWPCs), Cherenkov detectors, segmented wire ionization chambers, time-of-flight systems, Silicon pixel telescopes, and lead glass calorimeters.

FTBF also provides its services to resident physicists at Fermilab itself, and has tested detector components for large projects such as MINOS, MINERvA, BooNE and SeaQuest.[8] It is possible that the facility could have a future as a medical imaging apparatus testing site as well. The Test Beam Facility is an integral part of an active high-energy, high-intensity global effort and must be kept up to date to maintain the ability to accommodate its users.

1.2 Particle Tracking

The field of particle physics requires powerful detectors of extreme accuracy. Because particles are so infinitesimally small, it is important to be very familiar with the sensitivity of the equipment used in experimentation. One common way to ensure proper calibration of a particle detector is through the observation of the path traveled by a particle whose identity is known. Through careful particle tracking, it is possible to determine the efficiency of a detector with respect to a specific particle.

For humans to "observe" the passage of particles through a detector, we rely on a method of interpreting a series of electrical pulses using various electronic devices. Particle detectors are connected to data acquisition setups, which convert the pulses into readable data, which are then sent to a computer via a readout system. The readout system should simplify and organize particle data in such a way that it is easy to access and analyze.[3]

A classic yet still relevant particle tracking device used at FTBF is the multiwire proportional chamber (MWPC). These devices are comparatively inexpensive, quite robust, and are largely pre-existing, allowing the lab to repurpose older chambers. MWPCs consist of alternating planes of anode and cathode wires surrounded by a particular gas, usually a noble gas blend. As charged particles pass through the chamber, the gas becomes ionized and free electrons deposit on the sense wires.[9]

1.3 Readout Systems

From the 1980s until recently, the Test Beam Facility operated their MWPCs and other particle tracking devices using a setup built around the Nanocard, a piece of hardware responsible for amplifying and discriminating electrical pulses. The need for a new data acquisition system arose after the former system failed to adequately collect data from various particle tracking experiments.

The Nanocards were read out via numerous ribbon cables connected to a parallel CAMAC crate. Each ribbon had thirty-two pins and supported two μ-metal and ferrite shields to block extraneous electromagnetic fields from being read out with the data. These shields were heavy in comparison with the strength of the cabling pin connections and often caused the cabling to become disconnected or to have irreparably bent pins.

Another recurring problem with the existing system concerns inadequate and aging grounding wire.

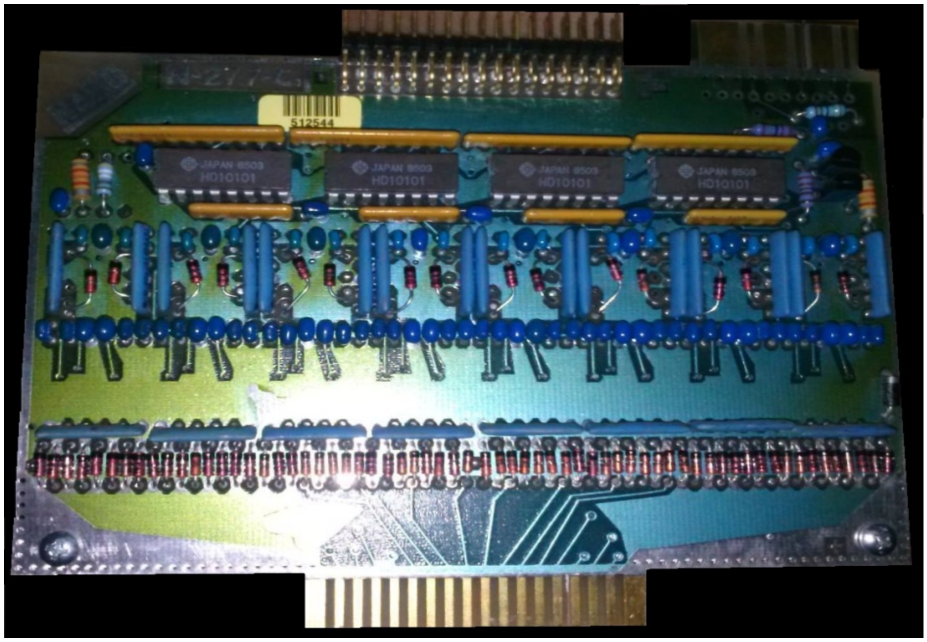

Figure 1: Nanometrics N-277 16-Channel Amplifier and Discriminator Instrumentation Amplifier

A new readout system is currently being built and will be ready for use by the time the Fermilab proton beam is again active, estimated to be in September 2013. The new electronic system features an integrated amplifying, shaping, discriminating, and charge measuring (ASDQ) card; reduced cabling; upgraded time-to-digital conversion apparatuses (TDCs); a new readout controller; updated CAMAC hardware; and new software architecture.

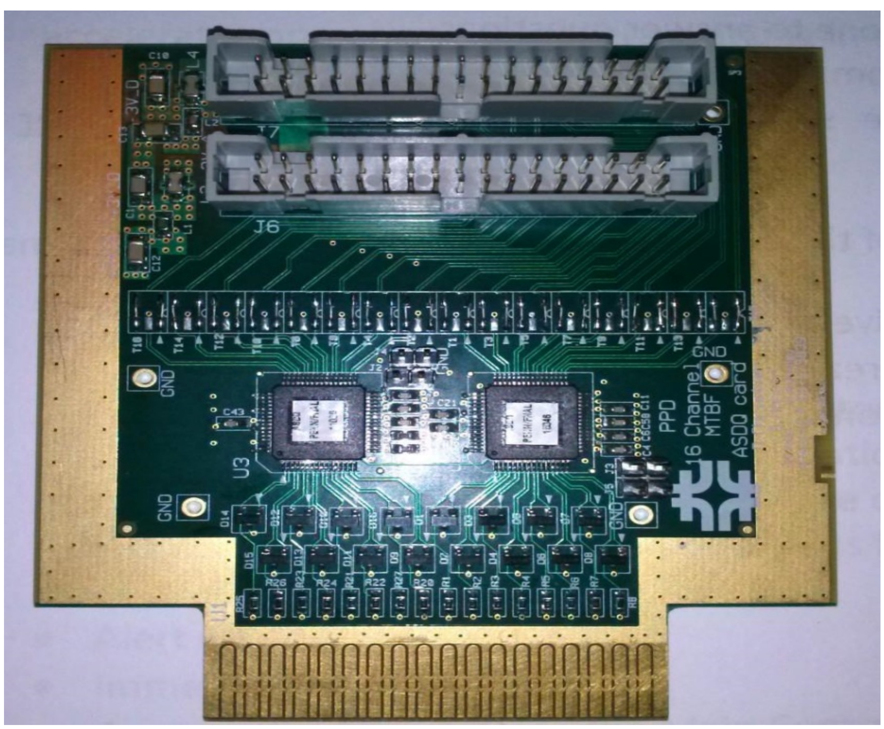

Figure 2: ASDQ ASIC

2. Progress

2.1 ASDQ ASIC

One crucial element to the upgraded readout system is the ASDQ integrated circuit developed at the University of Pennsylvania. This application-specific integrated circuit (ASIC) takes in the electrical pulse from the current carrying wire as input and buffers its preamplifier from extraneous external spikes, or noise. The signal is then amplified in the preamplifier where its charge information is converted into a voltage output. The signal is then "shaped" in a two-step process by first negating the signal from the ion tail of the particle, and then by zeroing the baseline signal in a process called baseline restoration (BLR). The shaped signal is then coupled to a discriminator to determine whether its value exceeds the threshold setting. If it is determined not to be noise, its charge is then measured using the dE/dx element, which implements time-constant signal integration. The ASDQ ASIC then transmits this information as output to a time-to-digital converter (TDC) to determine the time interval at which the event occurred.[2]

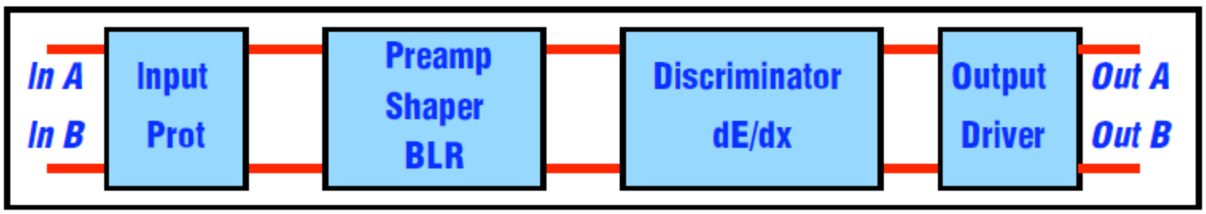

Figure 3:ASDQ Block Diagram

2.2 TDCs

Time-to-digital conversion devices are used for the precise determination of the time between two events, namely a "start" event and a "stop" event. In high-energy and high-intensity physics, TDCs can be used to identify particles, to measure the average lifetime of a particle, or to determine its time of flight.[3]

The electronic logic system used to sort legitimately sought-after particles from extraneous particles is called *triggering* and is highly dependent upon accurate time measurements.[3]

For a typical four multiwire proportional chamber setup, there are sixteen TDCs to gather useful particle data. Each TDC contains a clock, which is set in synchronization with a clock inside the readout controller. Each clock is adjusted to account for cable delays and is set for event coincidence. The TDC features a phase-locked loop control system which allows accurate calibration with the frequency of a particle accelerator.

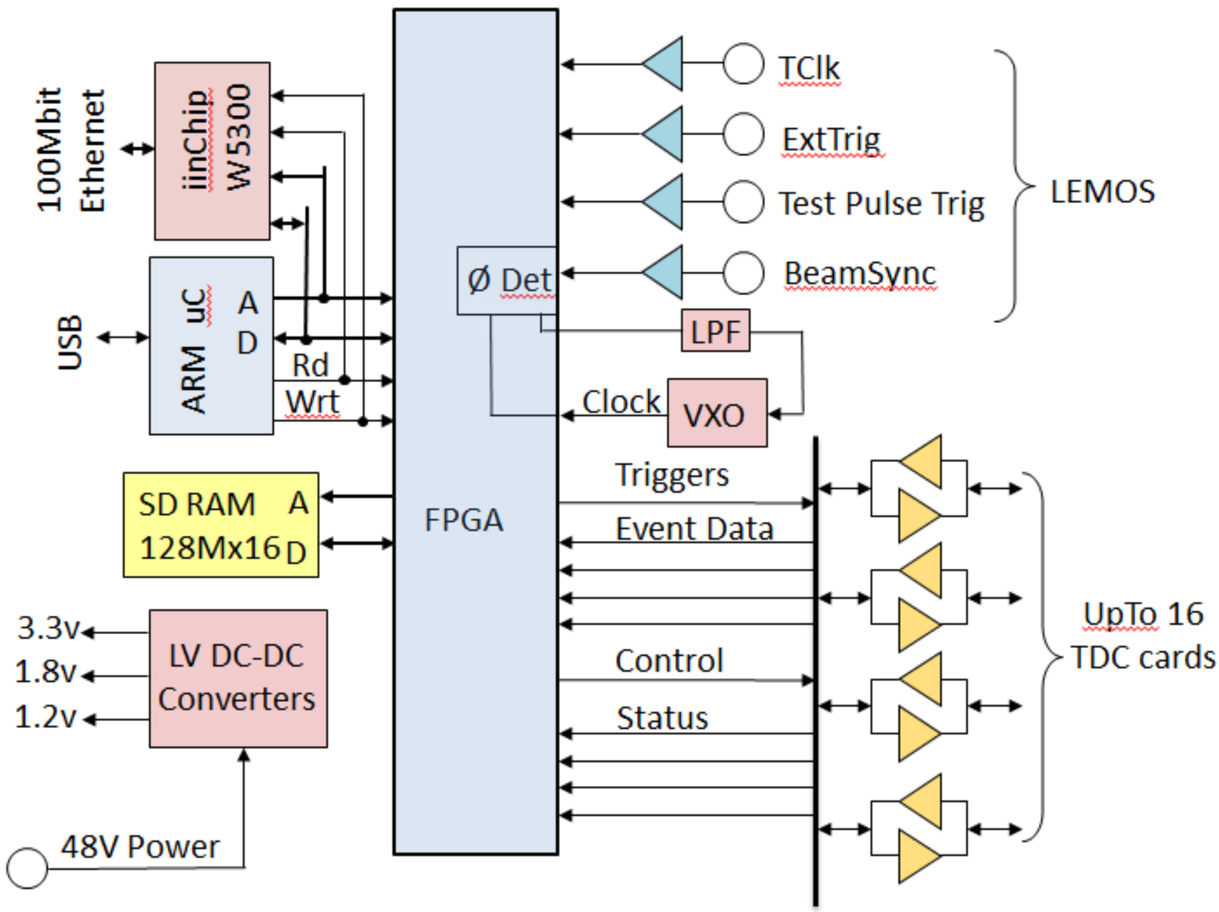

Figure 4: Controller Block Diagram with TDCs

2.3 Readout over Ethernet

Once the signal has been processed and determined to be significant (i.e., above threshold and in time with the trigger system), it is sent from the TDC to the readout controller. Meaningful, human-readable data can then be extracted provided a socket connection has been established between the client and the controller. The controller collects particle data from all TDCs and communicates with the client readout software used by the experimenters. The commands can all be classified as either a “Read” or “Write” and may therefore both send configuration data to as well as collect event data from the controller.

When a client makes a write( ) call, a configuration message is sent to the controller. This message can send binary data to specified TDC blocks, set values for eight thresholds, adjust current for baseline restoration, set separate test pulse heights for even and odd channels, set gate width, and set pipeline delay. This method can also disable specified channels if any seem to be problematic.

When a client calls the basic read( ) method, the controller sends to the client one solid block of data from all sixteen TDCs which begins with a global controller header of the entire data set. The header contains a global word-count followed by sixteen individual TDC subheaders to differentiate the data collected by each TDC. These subheaders contain TDC-specific word counts, number of triggers that occurred in the particular spill, and data events in order of TDC channel and trigger time.

Other "Read" type methods include getID( ) and getHelp( ). getID( ) returns status information for all TDCs to determine temperature, high voltage settings, and whether or not the controller is ready to send spill data to the client. getHelp( ) returns all possible commands that can be sent to the controller along with brief descriptions of what each method is responsible for.

2.4 Scintillator Paddle Testing

Three scintillator-photomultiplier tube paddles were assembled and connected to a system of signal-interpreting electronics to determine the sensitivity of each paddle at different high voltage settings. The purpose of these tests were to determine the optimal high voltage at which each counter should be set in order to maximize the system's efficiency.

The counters individually read into separate discriminator ports. The threshold for each counter was set to the lowest possible value, approximately 0.302 V. The discriminated output values were then read into a logic apparatus to determine the passage of a particle yielding a signal greater than the threshold value. The first logic port was set to be triggered upon the coincidence of a particle passage through the two control paddles, and the second logic port was set to be triggered upon the coincidence of all three paddles. The trigger count for the control paddles was compared to the trigger count for the set of paddles including the paddle to be tested. These values were used to determine the efficiency of the tested paddle over a range of high voltages.

2.4.1 Counter #1

- Smaller area than other counters (~5"x5"), causing lower efficiency compared to other counters
- While holding high voltage on other counters at 1700 V, efficiency plateaued for Counter #1 around 1600 V
- Beyond 1900 V, counter registers extraneous particles; voltage should be capped at 1900 V
- Optimal operational voltage suggested is 1700 V

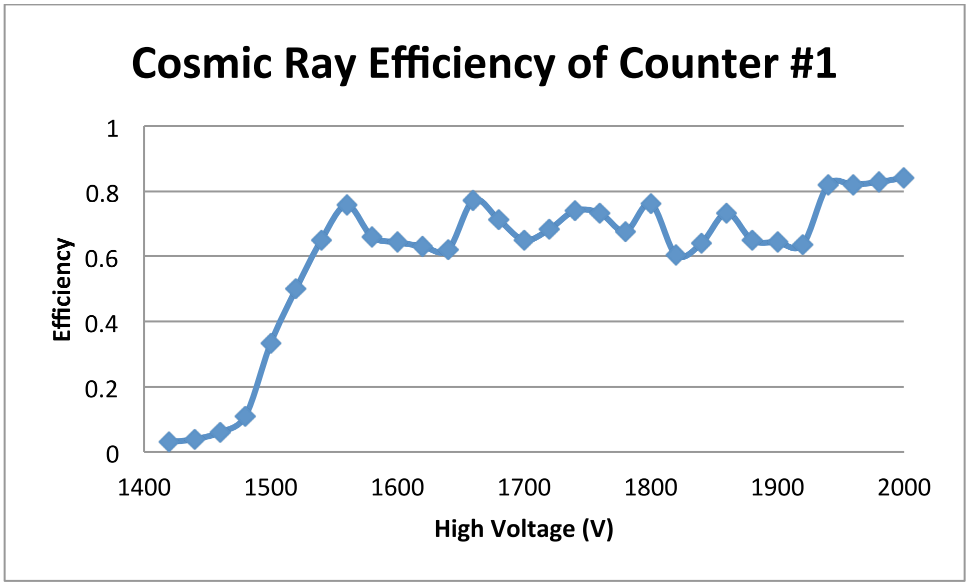

Figure 5: Counter #1 Efficiency

2.4.2 Counter #2

- ~6”x6” counter area
- While holding high voltage on other counters at 1700 V, efficiency plateaued for Counter #2 around 1700 V
- Beyond 2000 V, counter registers extraneous particles; voltage should be capped at 2000 V
- Optimal operational voltage suggested is 1700 V

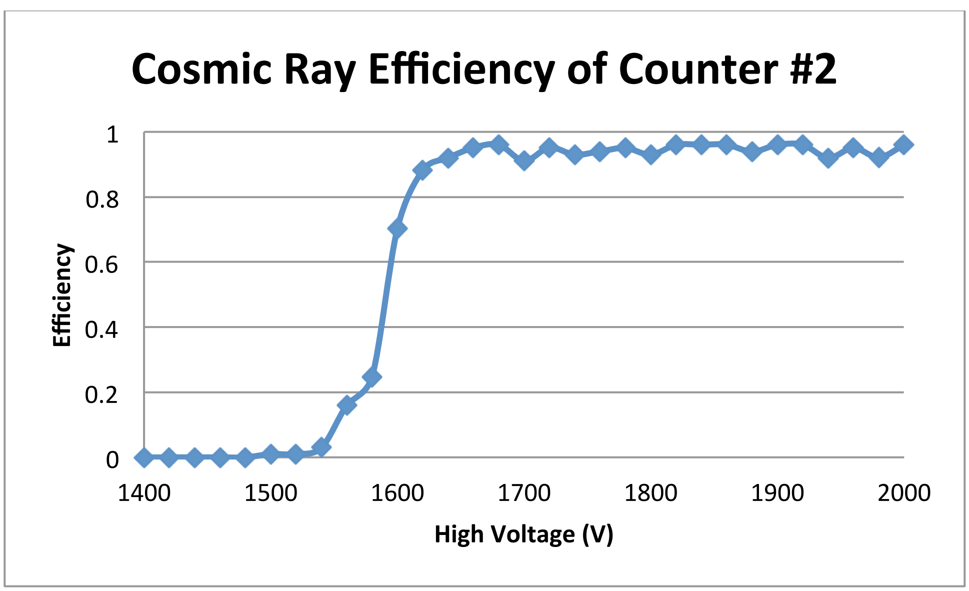

Figure 6: Counter #2 Efficiency

2.4.3 Counter #3

- ~6"x6" counter area
- While holding high voltage on Counter #1 at 1600 V and Counter #2 at 1800 V, efficiency plateaued for Counter #3 around 1400 V
- Beyond 1800 V, counter registers extraneous particles; voltage should be capped at 1800 V
- Optimal operational voltage suggested is 1400 V

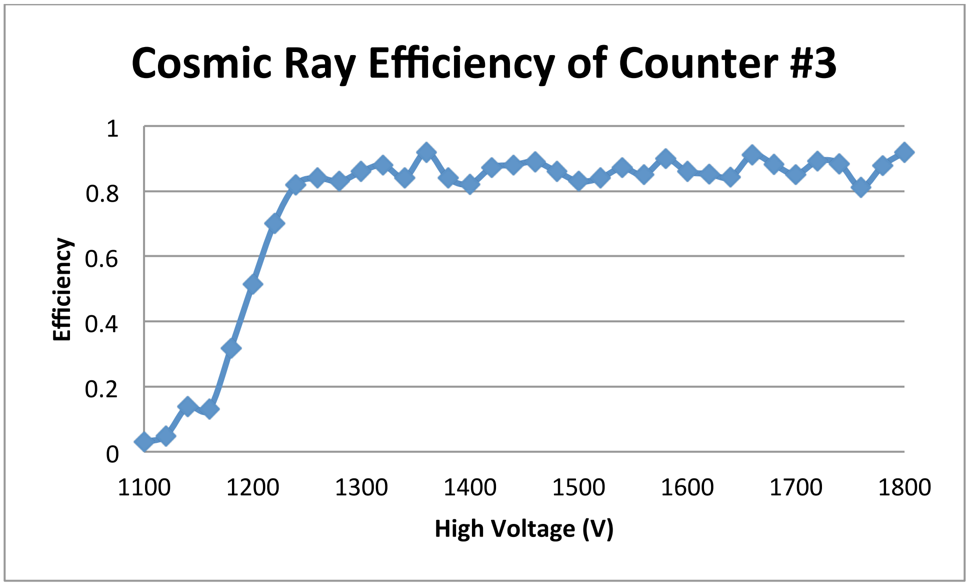

Figure 7: Counter #3 Efficiency

2.4.4 Operational High Voltage Suggestions

Each paddle has been tested for efficiency over a range of high voltages. It was determined that Counter #1 has a relatively high efficiency at 1700 V, Counter #2 has a relatively high efficiency at 1700 V, and that Counter #3 has a relatively high efficiency at 1400 V. The lowest voltages in their operational ranges should be used, and the counters have been labeled appropriately.

3. Future Work

The new readout system is nearly completed but cannot be fully implemented until the readout controller is in working condition. A cosmic ray test stand, consisting of a MWPC framed by scintillator-PMTs above and below, will be connected to the ASDQs, TDCs, readout controller, and data acquisition (DAQ) computer. Once the test stand has been set up, a trigger setting will be based on triple coincidence when a particle above the threshold value passes through the top scintillator-PMT, the MWPC, and the bottom scintillator-PMT. After the trigger system has been tested and calibrated, rigorous testing can begin between the new software and the readout controller. The goal of the software is to be self-documenting and to be capable of diagnostic debugging. This type of error handling will save time and will be easy to use.

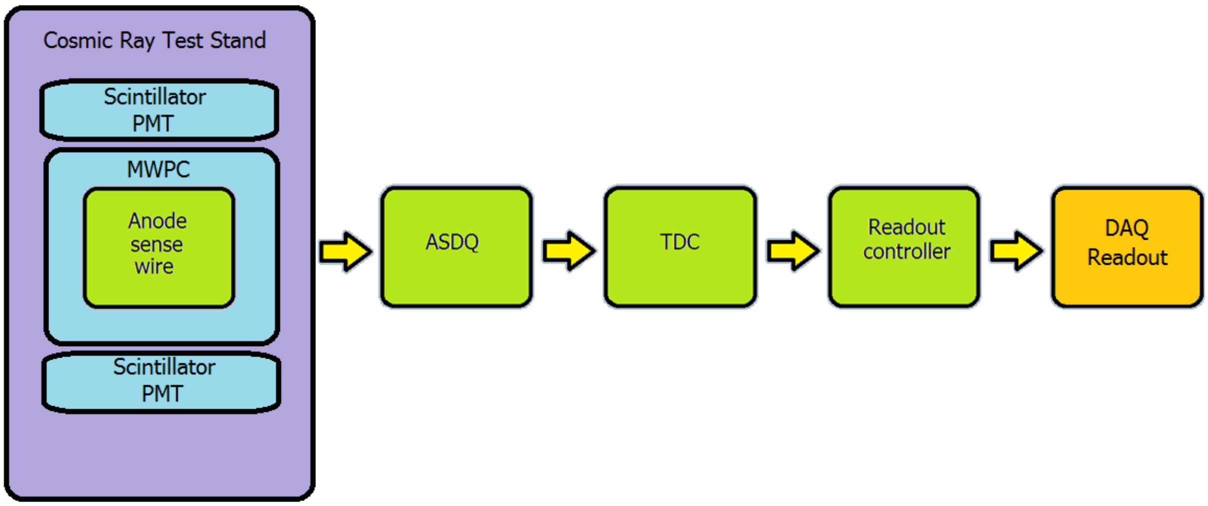

Figure 8: Overview of Particle Tracking Readout System

4. Impact on Laboratory Missions

The new readout system is designed to be efficient and to reduce long-term financial costs to Fermilab. The system boasts significantly reduced cabling due to the integrated functionality of the ASDQ boards and power over Ethernet. The improved software architecture features comprehensive diagnostic debugging, meaning fewer labor hours will be spent troubleshooting. Because of the updated TDCs and readout controller, data can be read in a more efficient manner once per spill instead of once per trigger. Finally, power usage is reduced by a factor of 100 as compared to the former system.[6]

5. Discussion

The redesigned readout system is nearly completed and lacks only the finalization of the new readout controller. Once the readout controller is in working condition, the particle tracking system will be immediately ready for data collection. By comparing the results of their devices with those of the particle tracking instrumentation available at FTBF, users can ensure they implement the correct thresholds, trigger timing, and identification methods for their projects.

6. Acknowledgements

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